High Resolution Schottky CdTe Diode Detector

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Abstract—

We describe recent progress on the use of Schottky CdTe diode detectors for spectrometry. The low leakage current of the CdTe diode allows us to apply a much higher bias voltage than was possible with previous CdTe detectors. For a relatively thin detector of 0.5–1 mm thick, the high bias voltage results in a high electric field in the device. Both the improved charge collection efficiency and the low-leakage current lead to an energy resolution of better than 600 eV FWHM at 60 keV for a 2×2 mm^2 device without any charge-loss correction electronics. Large area detectors with dimensions of 21×21 mm^2 are now available with an energy resolution of ∼2.8 keV. Long term stability can be easily attained for relatively thin (< 1 mm) detectors, if they are cooled or operated under a high bias voltage.

Keywords—**CdTe, CdZnTe, Pixel Detector, Gamma-ray, X-ray.**

I. Introduction

ENERGY resolution is one the most important characteristics of semiconductor detectors. The high stopping powers of Cadmium Telluride (CdTe) and Cadmium Zinc Telluride (CdZnTe), comparable with that of NaI(Tl) and CsI(Tl), are very attractive features for the next generation of gamma-ray detectors (see review [1], [2], and references therein). However, despite long-term efforts for their improvement, it is only recently that high resolution CdTe and CdZnTe detectors, with energy resolution better than a few keV (FWHM), have become available. Among them, CdTe and CdZnTe detectors with very low leakage current have been developed by several groups thorough the use of diode structure either by a blocking electrode or PIN structure[3], [4], [5], [6], [7].

We have reported a significant improvement in the spectral properties of CdTe detectors [5], [6], [8]. The detector is based on the high quality single CdTe crystal manufactured by ACRORAD, Japan. With the use of indium (In) and platinum (Pt) for the anode electrode and the cathode electrode, respectively, we can operate the detector as a Schottky diode (CdTe diode). The very low leakage current of the CdTe diode enables us to apply a high electric field to ensure complete charge collection in relatively thin (< 1 mm) devices. The improvement of the energy resolution by adopting the Schottky junction is drastic. Nevertheless, once the diode is formed, the detector shows the degradation of gain and resolution with time ($polarization$) under certain operating conditions. Both a high electric field of several kV cm^{-1} and a low operating temperature (below several °C) ensure stability on time scales longer than weeks [5], [6]. In this paper, we report the recent progress made on high resolution Schottky CdTe diodes and describe the results obtained from prototype detectors to be used in future space applications.

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II. THM grown CdTe detector with Pt/CdTe/Pt electrode configuration

The uniform charge transport properties of the wafer are very important aspects not only for fabricating large area strips or pixel detectors but also for constructing a large scale gamma-ray camera with many individual detectors. The CdTe crystal used here is the single crystal grown by the Traveling Heater Method (THM-CdTe) by ACRORAD [13], [14]. Grain boundaries and Te inclusions, which degrade the spectrum, are very rare. The electrical resistivity of ∼1×10^9 Ω cm (p-type) is achieved by compensating the native defects with Cl. The crystal is large enough to obtain (1 1 1)-oriented single crystal wafers with areas as large as 20× 20 mm^2.

Figure 1. shows the ^{241}Am spectrum obtained from Pt/CdTe/Pt at 25 °C with a 2mm × 2mm CdTe detector of thickness 1 mm together with the spectrum taken after 60 minutes. With an electrode configuration using platinum (Pt) for both side of electrodes, we can operate the detector as the usual "solid-ionization chamber" without polarity. According to the analysis described in [12], we obtained the mobility-lifetime products ($\mu\tau$) of $2-3\times10^{-3}$ cm^2/V and $3-5\times10^{-5}$ cm^2/V for electrons and holes, respectively. As shown in Fig. 1, the detector is free from problems with stability as long as the Pt/CdTe/Pt electrode configuration is used.

III. High resolution CdTe diode with In/CdTe/Pt electrode configuration

In the semiconductor detector, the number of electron and hole pairs produced by the interaction of X-rays and gamma-rays is large in comparison with that for scintillation counters. For 100 keV gamma-rays, the average number of pairs is as large as 22,000 for CdTe. If we assume a Fano factor of 0.15[16], the theoretical energy resolution is 500 eV at 100 keV. To reach this resolution, the most important factor is to reduce the electronic noise. The noise strongly depends on the leakage current, and so it is important to suppress this. One solution is to form a Schottky barrier at the interface between the semiconductor device and the electrode. With a combination of an ohmic contact on the other side of the detector, we can operate the detector as a diode, which exhibits very low leakage current when we apply the reverse bias.

Since the CdTe material grown by ACRORAD has p-type resistivity, a low work-function metal, such as indium (In), can be used to form a Schottky barrier. For the CdTe diode used

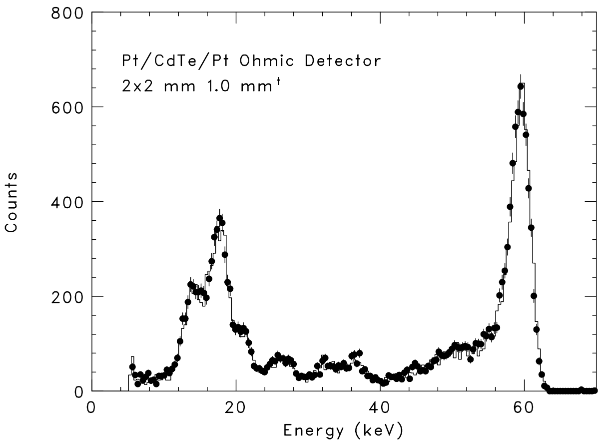

Fig. 1. ^{241}Am spectra obtained with the CdTe detector in Pt/CdTe/Pt electrode configuration operated at 25 °C (solid line). The detector has a surface size of 2mm × 2mm and a thickness of 0.5 mm. The time constant of the shaping amplifier is 0.5 μs. Filled circle shows the spectra obtained 60 min after the bias was applied.

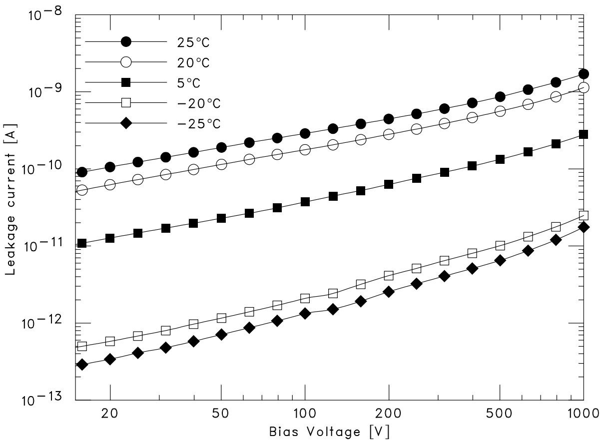

Fig. 2. Current-voltage (I-V) characteristics of the Schottky CdTe diode (In/CdTe/Pt electrode configuration) at different operating temperatures. The detector has dimensions of 2×2 mm^2 and a 1 mm thickness. A positive bias is applied on the In electrode.

here, In is evaporated on the Te-face of the wafer under vacuum [15]. On the opposite face (Cd face), a thin layer of Pt is formed by electro-less plating. As shown in Fig. 2 of [6], the detector shows current-voltage characteristics typical of a diode. A significant suppression of the leakage current is obtained in the reverse bias operation of the In (anode) /CdTe/ Pt (cathode) configuration. As shown in Fig. 2,the leakage current of the 2mm × 2mm × 1mm detector is 1 nA at 25 °C and 4 pA at −25 °C under a bias voltage of 300 V.

One possible drawback of the current Schottky CdTe diode is the long-term stability, especially for a thick detector [15], [5], [6] (thicker than a few mm). Despite the long-term stability we achieved for a CdTe detector with ohmic contacts (Pt/CdTe/Pt configuration), we experienced degradation of gain and resolution with time, very similar to the effect known as "polarization"[9], [10], [11], from the CdTe diode. Fig. 3 (top) shows the change of the ^{241}Am spectrum of a 1 mm thick CdTe diode operated at room temperature (25 °C) under a relatively low bias voltage of 400 V. The peak started to drift after several minutes of operation and smeared away after 60 minutes. After studies of various operating conditions, we finally found that a low operating temperature (below several °C) and/or a high electric field of several kV/cm (Fig. 3 (med)) ensures the stability on time scales longer than a week [5], [6]. (see also [3] for the effect of low temperature operation of different type of CdTe diode). For a 0.5 mm thick detector, only a very small change of the spectrum is noticed in operation at 25 °C , if the bias voltage of 400 V, which corresponds to an internal electric field of 8 kV/cm, is applied (Fig. 3 (bottom)). Quantitative discussion about the effect of high bias voltage for the suppression of polarization in the Schottky CdTe diode will be described in our next paper (Eisen et al. in preparation).

Little is known about control of the barrier height for CdTe and CdZnTe. This is different to the situation for GaAs, which is widely used in compound-type semiconductors in other fields. However, we have achieved some level of understanding of both the mechanism of the polarization and the surface conditions for obtaining good performance. According to recent studies in ACRORAD, the thermal process which is used during In evaporation plays a key role in realizing a stable contact at the In/CdTe interface. The detector shows the best performance if a thin InTe layer is formed at the interface as a hetero junction. We also found that the leakage current is high if we deposit In on the Cd-face [6], consistent with the fact that we need a Te surface to form a good InTe layer.

Dramatic improvement in both spectral resolution and stability can be obtained with a relatively thin detector operated at low temperature. As demonstrated in Fig. 4, an energy resolution of 530 eV (FWHM) for the 14 keV line from ^{241}Am is achieved from the detector with dimensions of 2mm × 2mm and a thickness of 1 mm, operated at −25 °C . The applied bias voltage is 300 V and the resultant leakage current was 4 pA. Under these conditions, the detector showed the same spectral performance for more than 24 hours.

Another important reason for adopting thin devices is that we can apply sufficient bias voltage to collect all charges produced in the detector. The 0.5 mm thick CdTe diode becomes fully active for applied voltages of 300 V. Under these operating conditions, even holes generated near the anode face can be completely collected [6], [17], [18]. The reduction of the low-energy tail even in 662 keV line from ^{137}Cs results in a resolution of 2.1 keV (0.3 %) (Fig. 3 in [17]), which is close to the theoretical limit by assuming a Fano factor of 0.15.

IV. Large area CdTe diode detectors

For the application of CdTe semiconductors to gamma-ray detection in fields such as nuclear physics and astrophysics, a detector capable of covering at least several hundred cm^2 is desirable. A simple solution is to use a large area CdTe diode with planar electrodes. We have developed such a detector, which has an area of 21.5 × 21.5 mm^2 using the 0.5 mm thick device. A picture of the detector, which was used for our balloon experiment in 2001, is shown in Fig. 5. The detector is mounted in a thin ceramic case, so that we can stack them to increase the effective area for energies up to 300 keV.

In order to obtain high energy resolution from a detector

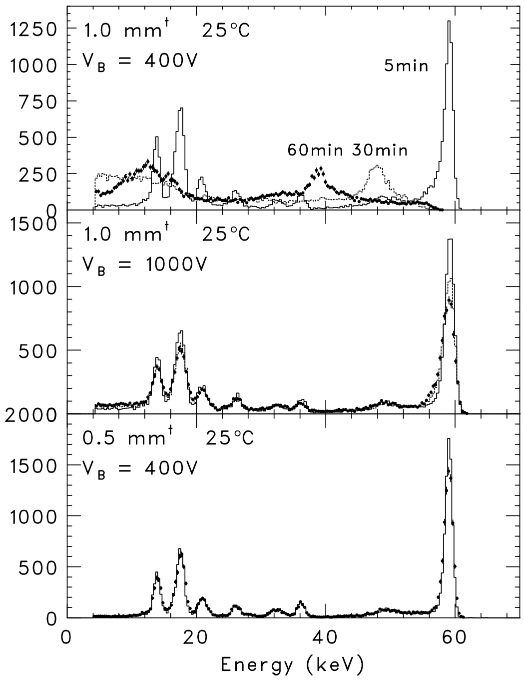

Fig. 3. The change of ^{241}Am spectra obtained from 1 mm thick and 0.5 mm thick CdTe diodes at different bias voltages. The detectors are operated at room temperature (25 °C); (top) 1 mm thick detector at the bias voltage of 400 V, (med) 1 mm thick detector at the bias voltage of 1000 V, (bottom) 0.5 mm thick detector at the bias voltage of 400 V. The spectra obtained when the bias voltage is applied (solid line), after 30 minutes (dashed line), and after 60 minutes (filled circle) are shown in the same figure. As the internal electric field increases, the detector becomes more stable.

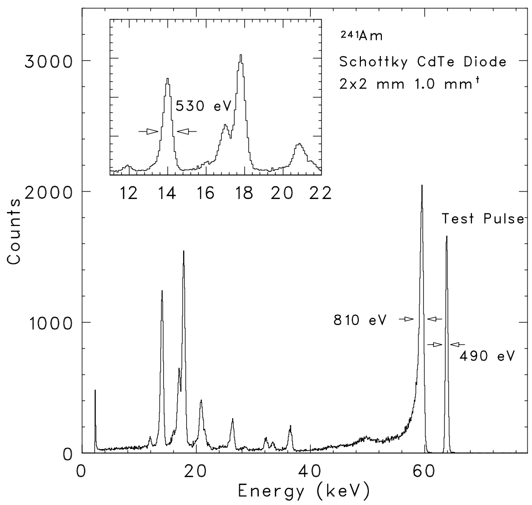

Fig. 4. ^{241}Am spectra obtained with the Schottky CdTe diode. The applied bias voltage is 300 V and the operating temperature is −25 °C . The energy resolution (FWHM) at 14 keV and 59 keV is 530 eV and 810 eV, respectively. The detector has a surface size of 2mm × 2 mm and a thickness of 1.0 mm. The signal is integrated by a Charge Sensitive Amplifier (CP-5109 by Clear Pulse) and shaped by an ORTEC 571 with the time constant of 3 μs. No rise time discrimination or pulse height correction technique was used.

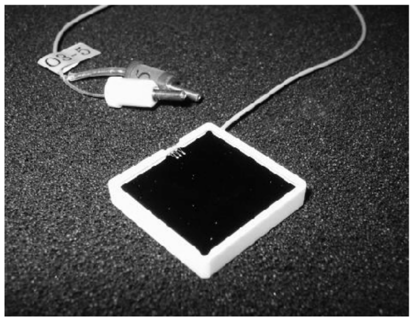

Fig. 5. Picture of the large Schottky CdTe diode with dimensions of 21.5 mm× 21.5mm × 0.5mm. High purity ceramic is used to minimize the background from the case, which could be a problem when the detector is operated in a very low background environment.

larger than a few cm^2, homogeneity throughout the detector plane is of particular importance. Fig. 6 shows ^{241}Am spectra taken through a tungsten collimator with a 1mm-hole. The detector was operated at −20 °C and under a bias voltage of 300 V. The detector has a capacitance of 100 pF and a leakage current of 30 pA. To minimize noise from the detector, the time constant of the shaping amplifier was set to 6 μs. As demonstrated in Fig. 6, the detector shows very nice resolution together with perfect uniformity. The location of the peak in the pulse height distribution agrees within 0.1% . The energy resolutions (FWHM) are almost identical and range from 2.71 keV to 2.78 keV. The energy resolution of 2.73 keV was obtained when we irradiated the whole area of the detector without using a collimator.

V. Application of CdTe diode for gamma-ray detection

A. A stacked CdTe detector

The stopping power for gamma-rays of CdTe is higher than NaI(Tl) or CsI(Ti), and therefore the energy resolution of $\leq$ 1% attained by the CdTe diode at moderate operating conditions is very attractive. However, when we increase the thickness of the CdTe/CdZnTe detector to improve the efficiency for high energy gamma-rays, the effects of incomplete charge collection become significant. As shown in Fig. 6 in [1], the gamma-ray peak structure is smeared out almost completely when we irradiate γ-rays from the anode face of a 2 mm thick CdZnTe detector with a planar electrode. We, therefore, proposed the idea of a stacked detector, in which several thin and large CdTe diodes are stacked together and operated as a single detector [8], [18].

Fig. 7 shows the energy spectrum of ^{133}Ba γ-rays obtained from the stack detector which consists of 10 layers with a total

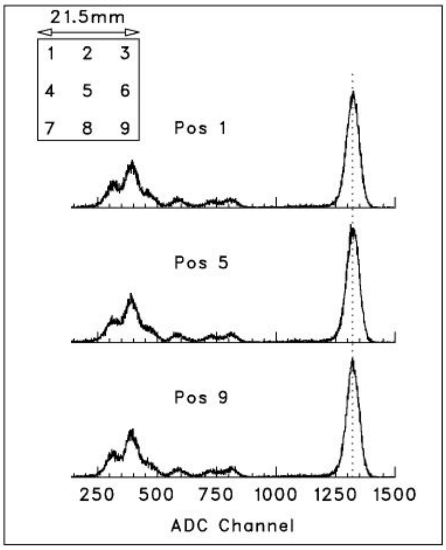

Fig. 6. ^{241}Am spectra obtained at locations 1, 5, and 9 of the large Schottky CdTe diode operated at $-20\,^{\circ}$C . The time constant of the shaping amplifier was 6 μs. The detector capacitance including the cable and the connector of the housing is measured to be $\sim$100 pF.

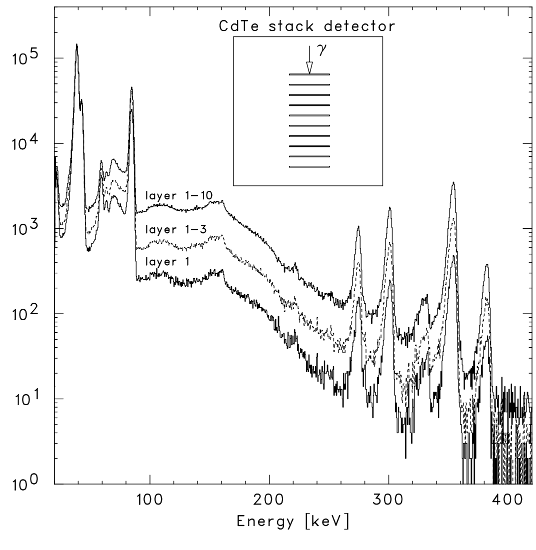

Fig. 7. ^{133}Ba spectrum obtained from the stacked CdTe detector at $-20\,^{\circ}$C under a bias voltage of 300 V. The stacked detector consists of 10 layers of a large Schottky CdTe diode with dimensions of 21.5mm $\times$ 21.5mm and a thickness of 0.5 mm. Together with the combined spectrum from all 10 layers, the spectrum from the first layer and the spectrum constructed from the first three layers are shown.

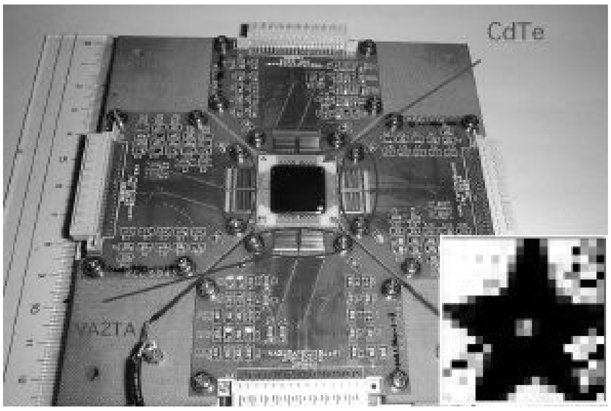

Fig. 8. Picture of a prototype CdTe pixel detector with the readout integrated circuits. The insert show the radiographic image of a lead object irradiated by gamma-rays from ^{57}Co.

thickness of 5 mm operated at $-20\,^{\circ}$C . The applied voltage is 300 V. In the stacked detector, the signal from each layer is processed independently. Instead of just summing all outputs from 10 layers, we select layers in which the signal exceeds the threshold level of the discriminator. The best energy resolution can be attained if we collect events which triggered only one layer, because we do not have a contribution from the noise in other layers. As clearly shown in Fig. 7, a very high peak-to-valley ratio can be obtained from the stacked detector. Since the detector is very modular, the detection of gamma-rays up to a few tens of MeV is easily achieved by simply adding more stacks.

B. The CdTe pixel detector

The high energy resolution of the CdTe diode is very attractive for hard X-ray and gamma-ray detection. In addition, good positional resolution is of great importance. We have developed the first prototype pixel detector using large area CdTe diodes (15mm $\times$ 15mm) [17]. A picture of the pixel detector system is shown in Fig. 8 together with the image of a lead object (a “star” with a hole in the center) placed on the back of the detector and irradiated with the 122 keV γ-ray line from a ^{57}Co source by selecting events under the 122 keV photopeak. By using a newly developed technology for gold-stud bump bonding, each pixel of the CdTe detector is bonded to the fanout board consisting of bump pads and patterns to route the signal from the pads. The signals from the detector are extracted and fed into 128 input ASICs which are wire-bonded to the fan-out board.

C. Large area 1024-array detector

Imaging detectors for gamma-rays, especially for gamma-rays with energies around the 511 keV annihilation line, are a major goal in various fields including medical applications. In order to have sufficient detection efficiency for the 511 keV line by CdTe and CdZnTe, the detector should be at least 5 mm thick. However, the current technology of making thick monolithic pixel detectors, for imaging detector with dimensions larger than 30mm $\times$ 30mm, is still immature in terms of the crystal fabrication and the readout electronics.

Therefore, we are now developing a large array detector com-

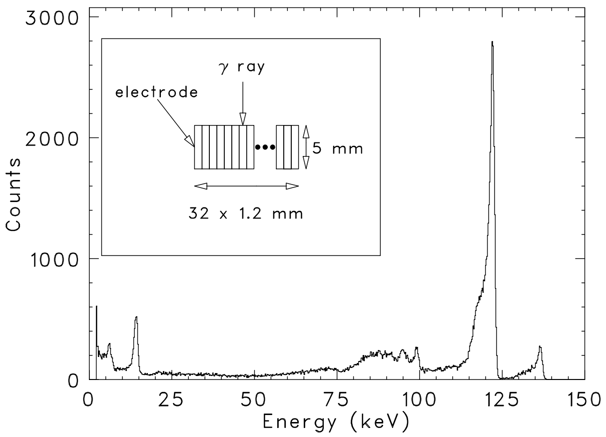

Fig. 9. Energy spectrum of ^{57}Co obtained with a single element of the 1024-array detector. The detector has dimensions of 1.2mm × 5.0mm and a thickness of 1.2 mm. As shown in the inserts, an edge-on geometry is used for each detector to improve the detection efficiency by keeping the good energy resolution of the CdTe diode. Thirty-two rows of 32 individual detectors are combined into one large detector.

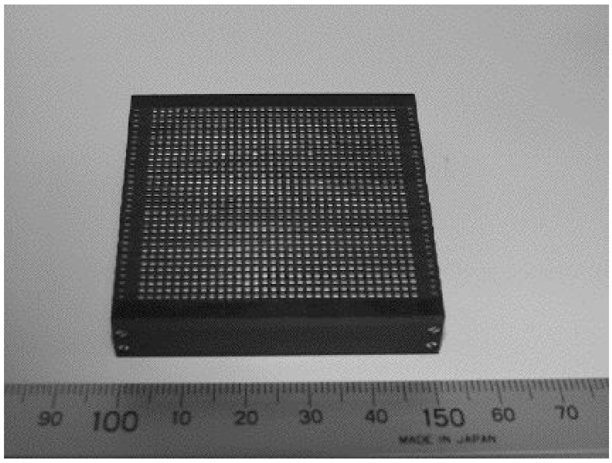

Fig. 10. A picture of the first prototype large 1024-array detector based on the high resolution CdTe diode. The pads from electrodes for the 1024 individual elements are shown. The total area covered by the detector is 38.4 × 38.4 mm^2.

posed of 1024 individual CdTe diodes, which will be used as a part of new generation Compton telescope planned at ISAS, Japan. The each detector has the dimensions of 1.2mm × 5.0mm and a thickness of 1.2 mm (Fig. 9). As shown in the insert of ths figure, an edge-on geometry is used for the injection of gamma-rays. This geometry has an advantage over a face-on geometry, because the distance between the two electrodes can be kept small, and we can therefore apply the high bias voltage which is necessary to achieve the high energy resolution (by reducing the low energy tail) and also to sustain the long-term stability of the CdTe diode. As shown in Fig. 10, the detector has 32 rows, each consisting of 32 individual elements. The total area covered by the detector is 44 mm × 44 mm (including gaps between each element). The spatial resolution of 1.2 mm is given by the cross-section of the individual detector element. In comparison with the monolithic type detector with pixellated electrodes, the uncertainty of the position due to the charge sharing among the adjacent pixels does not take place. The energy resolution of 1.4 keV was achieved using a conventional pre-amplifier for operation at -20 °C . The development of the readout electronics based on a low-noise ASIC with many inputs is now underway. The application of the same type of the detector for medical applications has been reported elsewhere.

VI. Conclusion

With a Schottky junction developed on the Te face of a high quality CdTe semiconductor by evaporating indium, we have been able to achieve a CdTe diode featuring very high energy resolution. The detectors show the best performance when we use a relatively thin detector of < 1 mm. The high energy resolution of the CdTe diode is very attractive for hard X-ray and gamma-ray detection. Especially, a large CdTe diode with dimensions larger than 20 × 20 mm^2 has the potential to replace scintillation detectors due to its high stopping power and energy resolution of ∼3 keV at 100 keV. Many concepts based on high resolution CdTe diodes are now being investigated and prototype detectors are being developed. Commercial application of the Schottky CdTe diode is reported in [20].

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